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Original communication

Head and neck injury patterns in fatal falls: Epidemiologic and biomechanical considerations

Michael D. Freeman, PhD MPH, Affiliate Professor [a,b,c,*],
Anders Eriksson, MD PhD, Professor [b],
Wendy Leith, MS, Statistician with Forensic Research & Analysis [a]

[a] Department of Public Health & Preventive Medicine, Oregon Health & Science University, Portland, OR, USA
[b] Section of Forensic Medicine, Umeå University, Umeå, Sweden
[c] Department of Forensic Medicine, Aarhus University, Aarhus, Denmark

A R T I C L E I N F O

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A B S T R A C T

Fatal falls often involve a head impact, which are in turn associated with a fracture of the skull or cervical spine. Prior authors have noted that the degree of inversion of the victim at the time of impact is an important predictor of the distribution of skull fractures, with skull base fractures more common than skull vault fractures in falls with a high degree of inversion. The majority of fatal fall publications have focused on skull fractures, and no research has described the association between fall circumstances and the distribution of fractures in the skull and neck. In the present study, we accessed data regarding head and neck fractures resulting from fatal falls from a Swedish autopsy database for the years 1992–2010, for the purposes of examining the relationships between skull and cervical spine fracture distribution and the circumstances of the fatal fall.

Out of 102,310 medico-legal autopsies performed there were 1008 cases of falls associated with skull or cervical spine fractures. The circumstances of the falls were grouped in 3 statistically homogenous categories; falls occurring at ground level, falls from a height of <3 m or down stairs, and falls from ≥3 m. Only head and neck injuries and fractures that were associated with the fatal CNS injuries were included for study, and categorized as skull vault and skull base fractures, upper cervical injuries (C0–C1 dislocation, C1 and C2 fractures), and lower cervical fractures. Logistic regression modeling revealed increased odds of skull base and lower cervical fracture in the middle and upper fall severity groups, relative to ground level falls (lower cervical <3 m falls, OR = 2.55 [1.32, 4.92]; lower cervical ≥3 m falls, OR = 2.23 [0.98, 5.08]; skull base <3 m falls, OR = 1.82 [1.32, 2.50]; skull base ≥3 m falls, OR = 2.30 [1.55, 3.40]). C0–C1 dislocations were strongly related to fall height, with an OR of 8.3 for ≥3 m falls versus ground level. The findings of increased odds of skull base and lower cervical spine fracture in falls from a height are consistent with prior observations that the risk of such injuries is related to the degree of victim inversion at impact. The finding that C0–C1 dislocations are most common in falls from more than 3 m is unique, an indication that the injuries likely result from high energy shear forces rather than pure tension, as previously thought.

1. Introduction

Death due to blunt trauma often involves injury to the head and neck.[1,2] A fatal impact to the head can result in a skull or cervical spine fracture, or both, depending on a number of factors, and death is typically due to concurrent injury to the central nervous system.[3,4]

Prior authors have described the "rule of the hat brim" as a basis for correlating an injury mechanism with a skull fracture location. Generally, when the fracture results from an object striking the head, the injury is more likely to be local to the point of contact, typically above the "hat brim" in the skull vault, depending largely on the size, shape, and stiffness of the object, as well as the force of the impact.[5–7] If the injury mechanism results from the head striking an object, as commonly seen in falls, then the injury

* Corresponding author. Department of Public Health & Preventive Medicine, Oregon Health & Science University School of Medicine, 425 NW 10th Ave, Suite 306, Portland, OR 9720, USA. Tel.: +1 971 255 1008; fax: +1 971 255 1046.
E-mail address: forensictrauma@gmail.com (M.D. Freeman).

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location can also be remote from the site of contact, i.e. below the hat brim; in the skull base or the cervical spine.[8,9] A number of prior investigations have indicated that head and neck fracture injury location in a fatal fall is likely dependent on a number of factors, including the degree to which the inertial forces from the victim's body contribute to the injury forces at the neck and skull.[2,3,10,11] It has been noted that when the body is inverted during a fall, e.g. with a fall down stairs or from a low height above ground level, at the point of impact the head is momentarily stopped while the inertia of the body moving toward the impact point continues to load the neck and skull base, thus increasing injury risk to these areas.[11,12] Depending on the degree of padding of the impacted surface there may be little or no evidence of injury where the head made contact. With such injury mechanisms, the site and nature of the injury location is dependent on the degree that the victim is inverted at the point of impact, as well as the contact point and angle of the head relative to the spine, i.e. the degree of flexion or extension.[13]

The available literature on fatal falls and head and neck injury is largely split into smaller studies that provide detailed information on fracture location and type, but often less information on the injury mechanism,[14–16] and larger studies that describe fall height but which tend to give less specific information on the fracture location and type.[17–19] In one older study the authors gave detailed descriptions of head and neck fracture distribution versus fall height among 63 autopsies, but the study group included only one case of cervical spine fracture.[20] Few of the studies have described or noted the degree of inversion of the victim at the point of impact. One exception was a recent study of 291 fatal falls in which the injury pattern of the decedents was compared for falls from height versus down stairs versus at ground level.[10] While the authors did find that falls that were more likely to involve inversion of the victim were also more likely to result in skull base fractures, they did not describe how this finding might relate to injuries to the cervical spine. We are unaware of any published research on fatal falls that have examined the correlation between fall circumstances, and specifically the degree to which the victim is inverted, and the distribution and type of skull and cervical spine fracture.

In the present study we present an examination of head and neck injury patterns and fall circumstances, based on data abstracted from an autopsy database.

2. Materials and methods

The Swedish database of medico-legal autopsies performed during 1992 through 2010 (19 years) was queried for all cases in which a fatal CNS injury was deemed by the examining forensic pathologist to be associated with a fracture of the skull or cervical spine. This database contains information from autopsies performed at 6 departments of forensic medicine in Sweden, at which approximately 5400 medico-legal autopsies are performed annually. The autopsies are described in a national database, which contains detailed information on all autopsies performed in Sweden from 1992 through the present time. The database contains information regarding, among other things, the demographic characteristics of the decedent, cause and manner of death, autopsy findings, and information regarding the circumstances associated with the fatal incident.

File information that was accessed included the date of death, age and sex of the decedent, manner of death (natural, accidental, homicidal, or suicidal) and the diagnosis of the skull or cervical spine injuries determined to be associated with the cause of death. Cases with more than one skull or spine fracture listed as being associated with the cause of death, with an undetermined or missing manner of death, or in which the decedent was less than 15 years of age, were excluded from the analysis. The cases were then categorized by the circumstances of the injury, which included falls, traffic crashes, being struck by an object, and crushing. The falls were further categorized by height fallen and whether they occurred on stairs. The location and type of injury was then cross-tabulated with the manner of death and the circumstances of the fall. Various categories of fall type or height that were found to be homogenous were collapsed.

Injuries that were unique to a particular fall category were then identified using a Chi-square or Fisher's exact test, depending on the size and distribution of the sample analyzed. Finally, odds ratios and associated Wald confidence intervals were calculated for the various fracture types and locations relative to the injury mechanism using logistic regression modeling, while adjusting for age, sex, and year of injury (Version 9.2; SAS Institute Inc., Cary, NC).[21]

All personal identifiers were redacted from the study material to maintain the anonymity of the decedents, and the study was carried out in compliance with the relevant laws and ethical guidelines.

3. Results

There were a total of 102,130 medico-legal autopsies performed in Sweden from 1992 through 2010, all recorded in the database. Of these, there were 5744 (5.6%) autopsies in which a cervical spine fracture or skull fracture was listed as being associated with the cause of death, with 5282 cases fitting the inclusion criteria.

Among all the included cases, the average age was 49.1 years (S.E. 21.7), and 72.9% of the victims were male. The manner of death among the majority of the autopsies was deemed accidental (83.4%), followed by suicidal (8.3%) and homicidal (2.6%) (Table 1). The most common fracture diagnosis was skull base fracture (41.6%), followed by skull vault fracture (37.5%), and upper cervical (C1 and C2) fracture (14.7%). The least common fracture diagnosis was in the lower cervical spine (C3 to C7) (6.2%). The upper cervical injuries were subcategorized as C0–C1 dislocations (48.8%), C2 fractures to the dens (22.1%) or neural arch (16.4%), and C1 fractures (12.8%). The fracture type with the highest average age and proportion of females was dens fractures (62.7 years and 42.1%, respectively). The injury type associated with the lowest age was C0–C1 dislocations (44.7 years). The largest proportion of males was observed among the skull vault fractures (75.3%).

Table 1
Summary statistics of autopsy database study population by manner and circumstances of death, and location of injury (S.E. = standard error of the estimate).

	N	% Female (S.E.)	Age (S.E.)
Total sample	5282	27.1 (0.6)	49.07 (21.7)
Manner			
Accident	4407	27.0 (0.7)	49.74 (22.1)
Homicide	137	35.8 (4.1)	50.09 (17.8)
Suicide	439	35.1 (2.3)	44.83 (19.7)
Cause			
Crash	3270	28.8 (0.8)	44.09 (21.5)
Crush	56	7.1 (3.4)	43.02 (18.0)
Fall	1628	25.7 (1.1)	59.00 (19.3)
Strike	202	24.8 (3.0)	51.60 (17.5)
Injury location/type			
Upper cervical	775	36.5 (1.7)	51.22 (21.7)
C0–C1 dislocation	378	37.3 (2.5)	44.66 (19.4)
C1 fracture	99	31.3 (4.7)	49.86 (22.5)
C2 – dens fracture	171	42.1 (3.8)	62.74 (21.1)
C2 – neural arch fracture	127	30.1 (4.1)	56.00 (21.0)
Lower cervical fracture	329	28.6 (2.5)	55.86 (21.2)
Skull base fracture	2195	25.6 (1.0)	45.72 (21.6)
Skull vault fracture	1983	24.7 (1.0)	50.83 (21.3)

The subgroup of decedents who died as a result of a fall was 1628 (30.8% of the total), and the average age in this group was 59.0 years (S.E. 19.3), with 74.3% of the victims male (Table 1). Falls accounted for 61.4% of the suicides, 4.5% of the homicides (there were only 6 such cases), and 28.0% of the accidental deaths in our series.

There was sufficiently detailed information to categorize the fall height or circumstances in 1002 of the cases, consisting of 820 (81.8%) skull fractures (450 skull vault and 370 skull base), and 182 (18.2%) cervical spine fractures (109 upper and 73 lower cervical). The majority (62.4%) of the upper cervical fractures were to C2 (43 dens and 25 neural arch fractures), followed by 23 (21.1%) fractures of C1, and 18 (16.5%) cases of C0–C1 dislocation.

Following examination of the data, falls were grouped in 3 categories by fall height and likelihood of inversion of the decedent at the time of impact as follows; ground level falls (low energy and low probability of inversion); staircase falls and fall distance of above ground but <3 m (low to moderate energy and high probability of inversion); and, falls of ≥3 m (high energy, moderate to high probability of inversion). The two latter categories resulted from the initial examination of various subcategories (i.e. stairway falls and <3 m falls, falls of various heights above 3 m) that were subsequently collapsed into their current form following statistical analysis for homogeneity. The frequency of injury type in each of the fall categories was grouped by proportion of all injury types, first by skull vault and base and upper and lower cervical spine, and then by the subcategories of upper cervical injuries (Figs. 1 and 3, respectively), and then by the proportion of each injury type accounted for by the fall type (Figs. 2 and 4). As an example, lower cervical fractures accounted for only 10.3% of all of the fractures occurring in the <3 m category, but the <3 m category accounted for 64.4% of all lower cervical fractures.

The category of falls accounting for the most cases was <3 m (45.5%), followed by ground level (31.5%) and then ≥3 m (23.0%). The skull vault was the most common fracture location in fatal ground level falls at 59.8%, versus 38.4% and 37.4% in the <3 m and ≥3 m groups, respectively (Fig. 1), whereas skull base fractures showed a direct relationship to fall height, comprising 27.5%, 38.8%, and 46.1% of the injuries occurring at ground level, <3 m, and ≥3 m falls, respectively ($p < 0.0001$). There were no similar patterns observed among the lower cervical fracture group or upper cervical fracture group as a whole. The highest frequency of each injury type was seen in the <3 m group for skull base, lower cervical, and upper cervical categories (47.8%, 52.3%, and 64.4%, respectively). In contrast, ground level falls accounted for the largest proportion (42.0%) of skull vault fractures ($p < 0.0001$) (Fig. 2).

Among the upper cervical fracture subgroup, there were substantially more C0–C1 dislocations seen in ≥3 m falls (the injury accounted for 50.0% of the total at this level vs. 7.0% and 7.1% in <3 m and ground level, respectively) (Fig. 3). As was the case with skull base and lower cervical fracture groups, the <3 m category accounted for the largest proportion of injuries in each of the upper cervical fracture subgroups, excepting C0–C1 dislocations, of which 66.7% occurred in the ≥3 m group ($p = 0.0004$) (Fig. 4).

The results of the subgroup analyses were used to construct statistical models of injury type based on injury mechanism. Among the decedents injured by falls, logistic regression modeling revealed increased odds of lower cervical and skull base fracture in the middle and upper fall severity groups, relative to ground level falls (lower cervical <3 m falls, OR = 2.55 [1.32, 4.92]; lower cervical ≥3 m falls, OR = 2.23 [0.98, 5.08]; skull base <3 m falls, OR = 1.82 [1.32, 2.50]; skull base ≥3 m falls, OR = 2.30 [1.55, 3.40]). C0–C1 dislocation injuries also demonstrated a strong relationship with fall height, with an OR of 8.3 for the injury in a ≥3 m fall versus ground level. In comparison with ground level falls, skull vault fractures were less probable in the other 2 categories, with an OR of 0.43 [0.32, 0.58] for falls of <3 m, and an OR of 0.31 [0.21, 0.46] for falls of ≥3 m. Adjusting for BMI did not alter these results, and thus this variable was left out of the final model (Tables 2 and 3).

4. Discussion

In the present analysis we identified a number of injury patterns in a population of autopsied victims of fall related blunt trauma that were correlated with certain types of fall circumstances. Presumably most, if not all, of the decedents sustained an impact to the

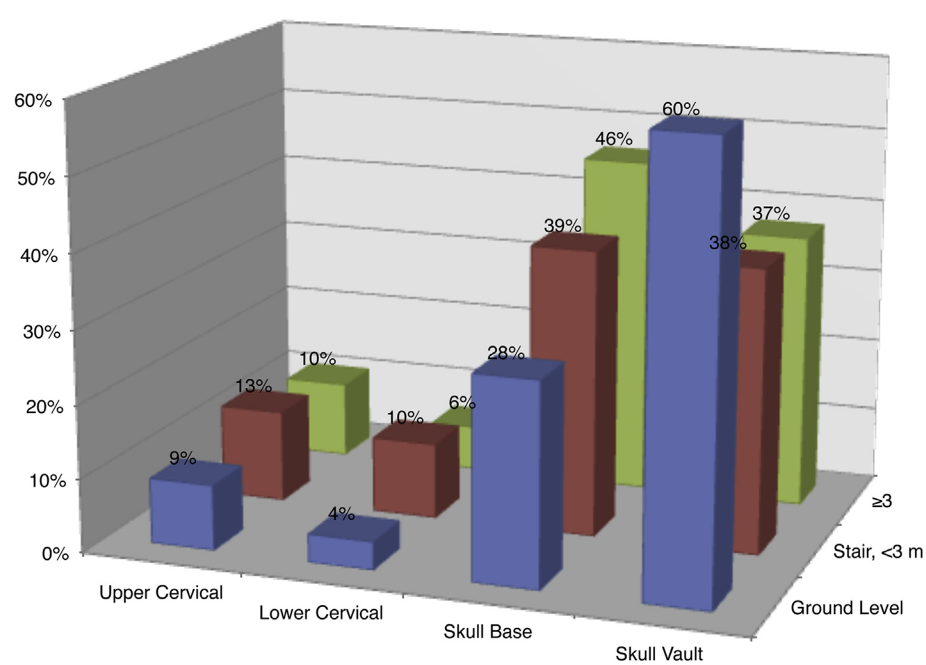

Fig. 1. Percent skull and cervical spine fracture location (upper cervical, lower cervical, skull base, skull vault) by fall category (ground level, above ground level but <3 m or on a staircase, ≥3 m).

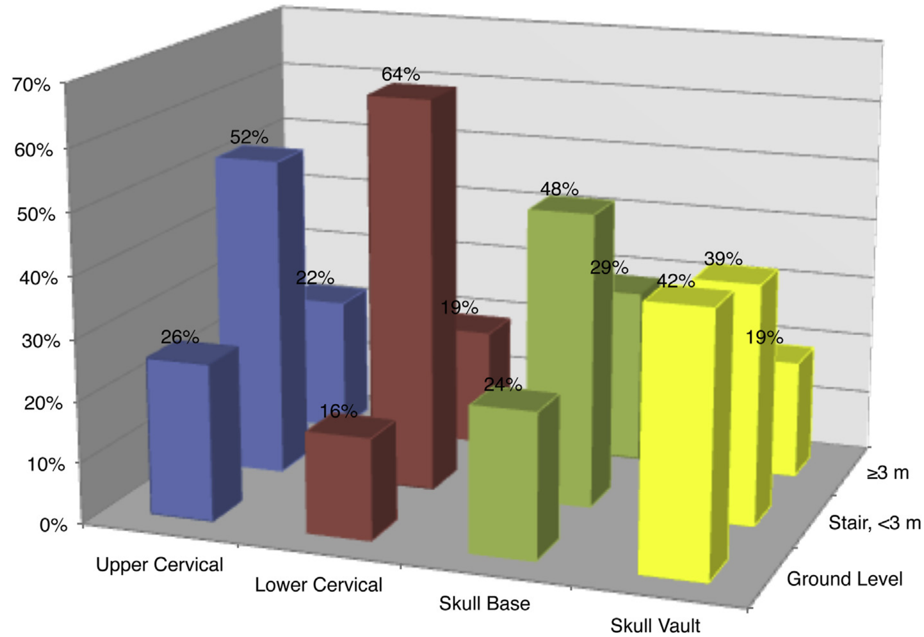

Fig. 2. Percent fall category (ground level, above ground level but <3 m or on a staircase, ≥3 m) by skull and cervical spine fracture location (upper cervical, lower cervical, skull base, skull vault).

head or face, and thus the fractures to the skull vault were more likely to have been proximate to the impact, and the fractures to the skull base and cervical spine were more likely to be remote from the anatomic site of the impact. Biomechanical experiments conducted on cadaveric specimens have demonstrated similar results; McElhaney et al. demonstrated that loads to the top of the head, similar to those that occur in a fall in which the victim is maximally inverted, produced both skull base and cervical spine fractures.[12]

One of the more prominent findings of our investigation was the observation that the proportion of skull base fractures was directly related to fall height, whereas the proportion of skull vault fractures was indirectly related to fall height, with the largest proportion, relative to other injury types, occurring at ground level. It makes sense that the risk of any fracture to the skull or cervical spine would increase as the height of the fall increases, as the energy of the fall is dictated by impact speed, and impact speed is a function of fall height. Based on this principle, one would expect that all skull fractures would increase proportionally as the impact energy associated with the fall increased. The observation in our data of a proportional decrease in skull vault fractures at greater fall heights is thus explained by factors aside from the impact energy of the fall. One such factor is the orientation of the body at the time of the

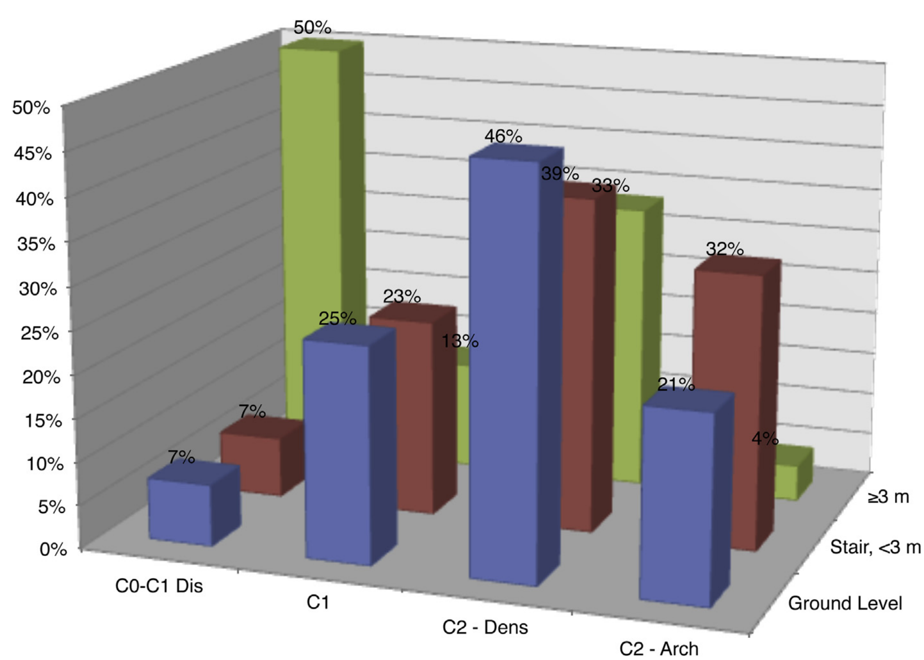

Fig. 3. Percent upper cervical spine injury location (C0–C1 [atlanto-occipital] dislocation, C1 fracture, C2 dens fracture, C2 neural arch fracture) by fall category (ground level, above ground level but <3 m or on a staircase, ≥3 m).

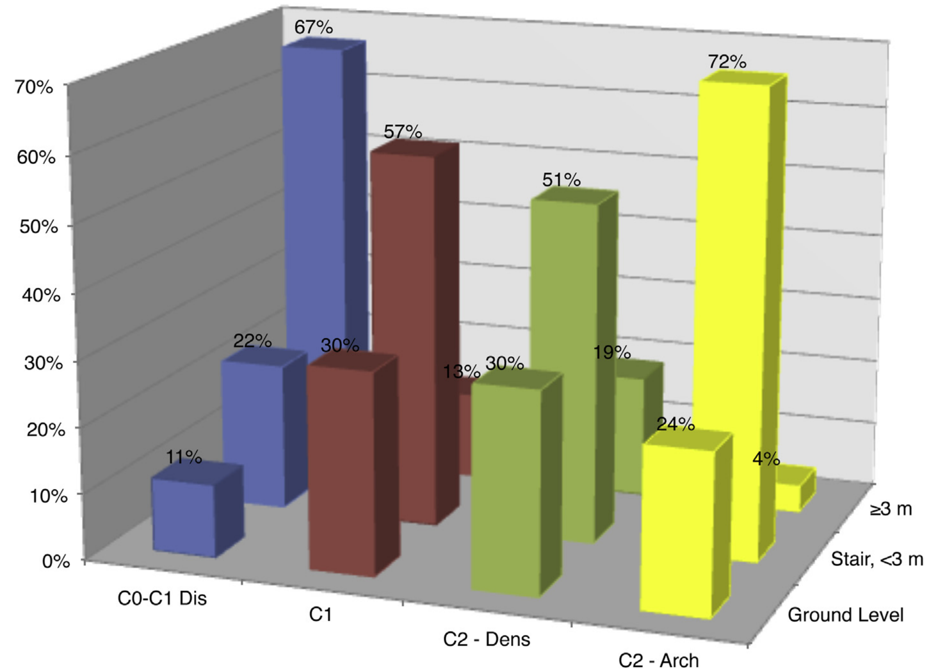

Fig. 4. Percent fall category (ground level, above ground level but <3 m or on a staircase, ≥3 m) by upper cervical spine injury location (C0–C1 [atlanto-occipital] dislocation, C1 fracture, C2 dens fracture, C2 neural arch fracture).

impact. Prior authors have noted that the degree that the body is inverted at the time of head impact is a predictor of higher risk of injury that is remote to the head contact point, i.e. skull base and neck versus skull vault. In comparison with ground level falls, falls down stairs and from heights above ground level are more likely to result in the victim being in an inverted position at the time of maximum loading of the head, with the orientation of the impact-related load generally in alignment with the long axis of the spine (Fig. 5).[10,11] Falls occurring at ground level, on the other hand, are more likely to result in impact forces that are relatively perpendicular to the spine and torso (Fig. 6).

Our observations are consistent with those described in prior investigations of the intersection of skull fracture location and the circumstances of a fall resulting in death. Thierauf and colleagues described 291 cases of fatal falls, including falls down stairs, falls at ground level, and falls from height, and compared the location of the observed injuries.[10] The authors noted that skull base fractures occurred in 47% of all cases, and were most commonly seen in falls from a height, followed by falls down stairs. The smallest proportion of skull base fractures occurred with falls at ground level. Preuss et al. noted that the most common location of fracture was the skull base in 75 cases of skull fracture observed in fatal falls occurring on stairs.[3]

Lower cervical fractures were substantially more likely in falls from height and on stairs in our study population as well. As was the case with skull base fractures, this observation is best explained by the greater likelihood of inversion of the decedent at the time of impact. In their review of cervical spine fracture mechanisms, Cusick and Yoganandan noted that injuries to the cervical spine are often associated with head impact, as the head comes into contact with a yielding surface and the neck then impedes the motion of the torso, as with a fall in which the body is inverted.[11] The authors noted that the three main biomechanical parameters that affect what type of cervical spine injury will result from a given trauma are the rate of force application, the magnitude of the applied force, and the force vector. They further noted that a flexion vector typically results in compression of the anterior part of the cervical spine and distraction of the posterior section of the cervical spine, and an extension vector causes compression of the posterior cervical spine and distraction of the anterior cervical spine. Nightingale and colleagues described the observation of a buckling phenomenon in the cervical spine when undergoing axial compression, generally involving extension collapse of the middle cervical vertebrae (C3-6) and flexion at the C7-T1 levels.[22] The degree to which the impacted surface is padded is also a factor in lower cervical fracture risk, as increased padding is associated with both decreased risk of skull vault fracture at the impact point and prolonged impact duration, resulting in a higher risk that the cervical spine will buckle during the load.[13]

Table 2
Adjusted Odds Ratios for skull vault, skull base, and cervical spine fracture risk by fall category (ground level, above ground level but<3 m or on a staircase, ≥3 m), with 95% Confidence Intervals. The* indicates statistically significant values.

	Upper cervical	Lower cervical	Skull base	Vault
Ground level	1	1	1	1
Staircase, <3 m	1.25 [0.77, 2.03]	2.55* [1.32, 4.92]	1.82* [1.32, 2.50]	0.43 [0.32, 0.58]
≥3 m	1.65 [0.90, 3.04]	2.23 [0.98, 5.08]	2.30* [1.55, 3.40]	0.31 [0.21, 0.46]

Table 3
Adjusted Odds Ratios for upper cervical spine fracture/injury risk (C0–C1 [atlanto-occipital] dislocation, C1 fracture, C2 dens fracture, C2 neural arch fracture) by fall category (ground level, above ground level but <3 m or on a staircase, ≥3 m), with 95% Confidence Intervals. The* indicates statistically significant values.

	C0–C1 dislocation	C1	C2 – dens	C2 – arch
Ground level	1	1	1	1
Staircase, <3 m	1.34 [0.24, 7.44]	1.21 [0.47, 3.10]	0.92 [0.45, 1.88]	1.84 [0.71, 4.74]
≥3 m	8.3* [1.72, 39.80]	0.61 [0.15, 2.53]	1.36 [0.53, 3.47]	0.34 [0.04, 2.96]

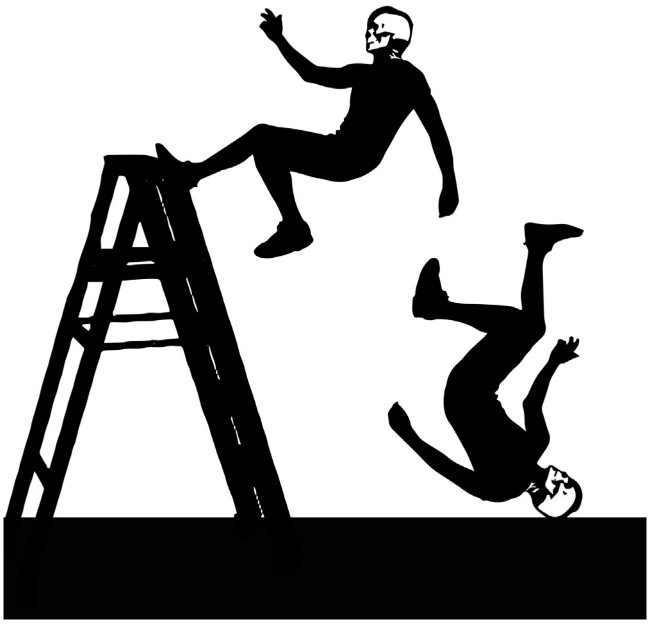

Fig. 5. Example of a fatal fall from a low height, sequentially demonstrating the initiation of the fall and early rotation of the victim, and associated inversion of the body at the time of head impact. The potential for axial loading and fracture of the skull base and cervical spine is relatively high, in comparison with ground level falls.

In the upper cervical spine the most common injury type in our study group was a C0–C1 dislocation, an injury that was approximately 8 times more likely in a fall from ≥3 m than at ground level. This finding appears to be inconsistent with the prevailing theory that C0–C1 dislocations result from pure tension forces,[2] an injury vector that is highly improbable in a fall from heights of ≥3 m. Indeed, aside from the forces exerted during a hanging with a long drop, pure tension forces at the cervicocranial junction would seem to be an extremely unusual occurrence. A reasonable explanation for our findings of greater risk of C0–C1 dislocation in falls from ≥3 m is that the injury results from a combination of both high impact energy and an injury force vector that is more perpendicular to the long axis of the spine, such as might occur with an impact to the occipital region with the neck flexed in an inverted victim. In such a scenario the injury would result from cervicocranial shear forces, and no component of pure tension would be present.

Fig. 6. Example of a fatal fall occurring at ground level, illustrating the head-torso orientation as roughly parallel with the ground at the time of head impact. The result is a relatively lower probability of impact-related axial loading and fracture of the skull base and cervical spine, in comparison with falls from a height or down stairs.

5. Study limitations

There were several limitations of our study; the most prominent was the lack of sufficient detail in the autopsy database that would allow for a more precise analysis of the biomechanics of the injury mechanism associated with the fall circumstances. The precision of our analysis would have been enhanced by a more detailed analysis of how the decedent fell and the degree of padding of the impacted surface. Of particular interest is exact information regarding the orientation of the decedent's body at the time of the impact, something that may only be accessible with video evidence. Such a study is reasonably feasible in the near future, given the increasing prevalence of video surveillance technology in public, work, and recreational settings.

An additional limitation in the present analysis is the fact that the only injuries included for study were those deemed by the examining forensic pathologist to be associated with the cause of death, which in all cases was injury to the CNS. This selection criterion would have biased the data in favor of the fractures most likely to be associated with fatal injury to the CNS, and thus explain the relative paucity of lower cervical fractures, which are more likely to occur without concurrent mortal injury to the brain or spinal cord than skull fractures and upper cervical injuries. Despite these limitations, the large numbers of cases afforded by the census nature of the autopsy database allowed for a high level of confidence in the stability of the findings reported herein.

6. Conclusions

In the present study we described the intersection between injury mechanism and skull and cervical spine fracture location in a large series of autopsied victims of fatal falls. Several general patterns of injury emerged from the analysis, as follows: 1) Fatal head injuries were 2–3 times more likely to be associated with skull vault fractures in ground level/lower energy falls versus higher energy falls and falls in which the decedent was more likely to be inverted at the time of impact; 2) Fatal head injuries were 2 or more times likely to be associated with a skull base or lower cervical fracture in fall circumstances in which the victim was inverted at the time of impact; and, 3) The most common upper cervical injury associated with fall-related fatal head injuries was C0–C1 dislocation, an injury that was strongly associated with falls from heights of ≥3 m. This last finding appears to be a new observation, and counter to the theory that such injuries can only result from pure tension at the atlanto-occipital articulation. Based on our results it is more likely that C0–C1 dislocations result from high energy shear forces.

Ethical approval
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Contributions of authors
MDF was responsible for the design, data access, data analysis and interpretation, and write up of the study manuscript. AE was responsible for the design, data access, write up, and editing of the study manuscript. WL was responsible for the data coding, statistical analysis, review and editing of the study manuscript.

Conflicts of interest

The authors declare they have no conflicts of interest.

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